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COLLIMATING OPTICAL MEMBER FOR REAL WORLD SIMULATION

TECHNICAL FIELD

The present invention relates to collimating displays for simulators for presenting objects that appear to be at a great distance.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

Not Applicable.

CROSS-REFERENCE TO RELATED APPLICATIONS

Not Applicable.

BACKGROUND

Simulation of the real world is implemented in a wide variety of applications ranging from vehicle training simulators to video games. The simplest simulators are those used, for example, in video games. Generally, such simulators utilize a video display presented on a cathode ray tube monitor or a liquid crystal display. Such displays are meant to simulate the appearance of an outside world view seen through a window. The analog of the real world window in a display is, for example, the face of the liquid crystal display. The display has dimensionality, motion characteristics and perspective characteristics similar to those of a video image produced by a video camera. Accordingly, images presented on these sorts of systems lack realistic image change responses to head movement, eye movement and the like.

For example, if one viewing the real world through a window moves one's head to the right or the left, an image which is at a great distance from the observer will appear to move to the right or left within the window. In other words, as the viewer moves his head, the scene through the window will change and the object will appear to be stationary even though the observer is moving. This is in contrast to a directly viewed cathode-ray tube display, such as that produced on a personal computer or television set, where the image is independent of user head movement.

A similar effect obtains in the case of user movement toward and away from the display. Such user movement results in radical changes in apparent image size. This is in contrast to the real world where objects at a relatively large distance (for example 100 meters) appear unchanged in size despite relatively small (for example 5-10 centimeters) head movements toward and away from the display.

The problem stems from the fact that the simulated scene on a display is located a relatively finite distance from the user, perhaps 40 cm. Accordingly, head movement of a few centimeters causes radical disparity between expected image position and actual image position. Nonetheless, such systems do enjoy a large measure of popularity in the civilian world, because the human brain is well trained by television to accept such displays. Nevertheless, such displays, while accepted by the human brain, fail to provide the numerous visual cues such as image movement, parallax, image size and the like, that inform and then guide reactions.

Accordingly, merely providing a picture-type display is not suitable for experience-based training, such as that required by aircraft pilots, watercraft pilots, seaman and the like, fighting vehicle drivers, astronauts, drivers, and so forth, as well as gunnery, navigation and other personnel associated with vehicles and fixed installations such as bunkers, communication facilities and defensive/offensive gun emplacements. In addition remote prescence systems requiring real world image response to movements of the viewer.

One approach to the problem is the use of focusing optics which receive light from an image source and collimate it, making it appear that the image source is at a, or, at least, close to a great distance away. Because light coming from optics which are at a great distance is substantially parallel, collimation of an image source before presentation to the eye of a viewer is an effective strategy to present the viewer with effective real world simulation which will be useful to train reflexes, responses, and the like.

Such displays generally involve the placement of the image source near the focal point of a focusing optic. For example, if the image source is the face of a cathode ray tube (CRT), the CRT face plate may be positioned in the focal plane of the

focusing optic. Accordingly, all light emanating from the face of the cathode ray tube and collected by the focusing optic will be presented as collimated, that is parallel bundles of light. While, in principle, refractive optics can perform this function, as a practical matter, the weight, thickness, and aberrations associated with refractive optics renders such an approach impractical. Accordingly, it is desirable to use reflective optics.

However, reflective optics present a multitude of challenges. For example, an image would generally be formed by having the source on the same side of the reflective optic as the observer. If the image is presented by folding the axis by the use of a partially reflective, partially transmissive planar optic, the assembly is clumsy and the presentation of adjacent assemblies complicated or impossible. While, in principle, one may replace the concave optic with a half-silvered concave member, holographic equivalent thereof, or the like, the direct view of the original image may destroy the usefullness of the effect.

Since the 1960's, simulator displays have been available which address the above problems with varying degrees of success. For example, the collimating simulation optic sold under the trademark Pancake Window provided a solution to this problem.

Such systems are described in United States Patent Number Re 27,356, and comprise a sandwich comprising a vertical polarizer, half-silvered concave optic, quarter-wave plate, planar beam-splitter, quarter-wave plate, and horizontal polarizer, which sandwich is coupled to an image source.

Generally, in accordance with this technology, an image source may be caused to pass light through a vertical polarizer. The light from the vertical polarizer passes

through a concave half-silvered focusing optic, which, in turn, passes image source light through a quarter-wave plate which gives the light clockwise (or right) circular polarization characteristics. The circularly polarized light is reflected off a beam-splitter (a half silvered planar mirror) which causes it to have reversed or counterclockwise circular polarization. The light which is now circularly polarized in a counterclockwise (or left) direction goes through the quarter-wave plate again, emerging as horizontally polarized light, which is, in turn, reflected by the concave reflective optic and passes through the quarter-wave plate again which restores it to a bundle of counterclockwise circular polarized light, which is transmitted by the beam-splitter with unaltered polarization and finally passed through a quarter wave plate which passes the light with a horizontal linear polarization characteristic. The output image is then passed through a horizontal polarizer.
Light which passes directly from the image source through the vertical polarizer and through the various optical elements will be vertically polarized and will be blocked by the final polarizer which passes only the intended horizontally polarized light bundle.

Such systems have seen a wide variety of applications, including various vehicle simulators, such as aircraft simulators, space vehicle simulators, and so forth. Image sources used with such systems include cathode ray tube displays, models, painted displays, and so forth.

However, in theory, every transmission through and reflection off a half-silvered optical member and certain transmissions through a polarizer involve a nominal fifty percent loss of intensity. This loss occurs two times at the focusing optic, twice at the beam-splitter and once at the first of the two polarizers. Accordingly, significant losses occur, as appears more fully below.

In principle, some of the disadvantages of collimating optical members for simulators may be addressed by systems comprising a sandwich of elements comprising a vertical polarizer, a quarter wave plate, a concave half-silvered focusing optic, and a cholesteric polarizer. See, for example, United States Patent No. 4,859,031. Generally, such systems work because the cholesteric polarizer has the characteristic of passing light with one circular polarization but transmitting light having the opposite circular polarization. However, such systems suffer from the inadequacy of the cholesteric polarizer which has a relatively narrow range of reflectivity and requires the use of, for example, three layers of optics, resulting in a relatively thick assembly forming the collimating optical simulator member, and presentation of images with multiple color components which are out of register with each other.

SUMMARY OF THE INVENTION

The present invention provides a collimating image-forming apparatus comprising a first linear polarizer, a first quarter-wave plate adjacent the first polarizer and having its fast and slow axes at substantially 45 ° to the plane of polarization of the first polarizer. A beam-splitting curved mirror has a convex surface adjacent the first polarizer and facing towards the first quarter-wave plate. A second quarter-wave plate is adjacent the concave side of the curved mirror. The second quarter-wave plate has its fast and slow axes oriented with respect to the corresponding axes of the first quarter-wave plate at angles substantially equal to a first integral multiple of 90°. A reflective-transmissive polarizing member is positioned adjacent the second quarter-wave plate. A second linear polarizer is adjacent the reflective-transmissive polarizing member. The second linear polarizer has its plane of polarization oriented with respect to the plane of polarization of the first linear polarizer at an angle substantially equal to a second integral multiple of 90°, both of the multiples being even or both being odd.

BRIEF DESCRIPTION OF THE DRAWINGS

The implementation of the invention may be understood in conjunction with the written description of the invention contained herein taken together with the following drawings, which illustrate only several embodiments of the invention, and in which:

Figure 1 is a diagrammatic exploded perspective view of the preferred embodiment of the inventive collimator, illustrating the position of the source and an observer;

Figure 2 is a diagrammatic cross-sectional view of the inventive collimator illustrated in Figure 1; and

Figure 3 is a diagrammatic cross-sectional view of an alternative embodiment of the inventive collimator similar to the view of Figure 2.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring to Figure 1, in accordance with the invention, a collimator 10 comprises a polarizer 12, having a vertical polarization orientation. Polarizer 12 transmits light to a quarter wave plate 14 which outputs right circular polarized light to focusing mirror 16. Focusing concave mirror 16 is a concave mirror having a half silvered surface 18 coated on a concave glass substrate 20. Concave mirror 16 is optically coupled to a second quarter wave plate 22 which is optically coupled to both concave mirror 16 and a panchromatic reflective/transmissive polarizer 24 which is optically coupled to both quarter wave plate 22 and horizontal polarizer 26. In accordance with the invention, it is noted that the horizontal and vertical polarizers may be at different angles, provided that they are substantially at right angles to

each other.

In accordance with the preferred embodiment of the invention, reflective/transmissive polarizer 24 is made using liquid crystal and photoimageable alignment materials coated in multiple layers onto a substrate such materials are available from Rolic Technologies Ltd. Reflective/transmissive polarizer 24 has the characteristic of reflecting vertically polarized light while transmitting horizontally polarized light.

Alternative structures providing the desired reflective/transmissive characteristic of polarizer 24 are multilayer biaxial structures such as those manufactured by 3M and known as DBAF Polarizer material.
Still another approach to achieve the desired reflective/transmissive characteristic of polarizer 24 is to use a wire grid polarizer, such as those manufactured by Moxtek.

It is noted that in accordance with the present invention, a panchromatic, that is full-color characteristic is desirable for polarizer 24, as well as the other elements in the inventive collimating display 10. In connection with this, it is noted that while optical elements 14 and 22 are referred to as quarter wave plates, they have different thicknesses at different wavelengths, but function to provide their effects across the visible spectrum to produce full-color simulation. This is on account of the fact that deviations in thickness from a true quarter wavelength are consistent in both optical elements 14 and 22 and the effects which they produce complement each other to function as described below with a full color characteristic.

The prior art collimating optical image forming apparatus as described in United States Patent No. Re. 27,356 has been a basic component in a wide variety of optical display and simulation systems. Nevertheless, apparatus described in United States

Patent No. Re. 27,356 is improved in accordance with the invention as a result of the optical design of the present invention. In particular, the prior art optical design generally provides a low transmission throughput in the general area of 2% or less of the light from the image source being used to create the simulation. While the losses can be compensated, to some extent, by using a brighter image source, the more powerful illumination tends to increase the perception of certain other negative consequences of the basic optical design.

More particularly, one consequence is the appearance of darkened, color shifted areas in the field of view of the display. These areas are typically located in the corners of the display's field of view. In accordance with the invention, this problem is solved by structuring the elements to compensate for variation of the angle of incidence on the one quarter wave retarder elements. In the prior art, the angle of incidence is altered by the spherical beam splitting optical element used to collimate the image for rays of light relatively far removed from the principal axes of the display field of view.

The optical design of the present invention stems, in part, from the understanding that the result is that the state of polarization is altered in these areas, from the uniform linear polarization that is desired, to a linear polarization that is rotated in angle relative to the desired uniform linear polarization, causing, to varying degrees, development of elliptical polarization particularly in the areas at the furthest distance from the principal axes of the display field. While this would not appear to be a problem on its face, the alteration of the polarization state, particularly in these areas, results in decreased transmission through the corresponding areas of the linear polarizer that is next encountered by light passing through the system.

There is also a shift in color hue in these areas because light in some portion of the

spectrum is attenuated to a greater extent than light in other portions of the spectrum. Other deficiencies prevalent in the usual embodiment of this type of apparatus are associated with the materials traditionally used in the manufacture of these devices. In particular the one quarter wave retarders and linear polarizers used are typically plastic film materials since heretofore these were the only such materials, available in sizes large enough to produce the large devices required of the typical application for such apparatus. Even so, for the largest devices, multiple pieces of the one quarter wave and linear polarizer materials must be used with the result that seams between the various pieces are noticeable in the display field of view. These plastic films must also be laminated onto other elements with various adhesives that are difficult to handle and which have the potential to suffer degradation with age. Furthermore, the materials from which one quarter wave retarders are made are typically stretched plastic films. Likewise, linear polarizer films also exhibit strain marks that are visible in the display's field of view. Since these materials are disposed at various angles in the construction of the apparatus, the result is a "cross-hatched" or "plaid" pattern of uneven illumination.

The improved apparatus which is the subject of this patent addresses the problems associated with the previously used materials by replacing the plastic film one quarter wave and linear polarizer films with liquid crystal materials directly coated onto other optical elements such as a flat beam splitting mirror incorporated in the inventive system as appears more fully below. One quarter wave retarders and linear polarizers formed by this technique avoid the necessity of having seams in large display devices and are essentially free of the strains that result in the "cross-hatched" or "plaid" pattern of non-uniform illumination. Use of such liquid crystal materials to form the optical elements of the inventive system, as described below, is known in the art and forms no part of the present invention.

In accordance with the present invention, one quarter wave retarders manufactured

with these liquid crystal materials may incorporate characteristics tailored to correct the darkened corner phenomenon that is a consequence of the original optical design. More particularly, in accordance with the invention, the characteristic of the one quarter wave retarder can be modified in several ways. In one possible modification, the one quarter wave retarder can be made less sensitive to the angle of the incident light by creating multiple layers of liquid crystal materials, each layer having a different angular orientation normal to the surface upon which it is created. Another possible modification is to vary the thickness of the liquid crystal material in specific areas, thereby varying the amount of retardation in these specific areas. Another possible modification is to vary the alignment of the fast and slow access of the retardation materials in specific areas.

Such structures may be formed using materials available from Rolic Technologies Ltd.

In general, a combination of these three altered retarder characteristics are needed to correct the phenomenon for the specific optical design of any particular example of the display apparatus. For convenience, any combination of the elements formed with the new liquid crystal materials and the more traditional materials can be used depending upon the requirements of the final apparatus. Furthermore, optical retarders and linear polarizers formed from liquid crystal materials can be produced on plastic film substrates. For certain embodiments of the improved display device, this may be a more convenient format.

In general, the design objectives in implementing a combination of one or more of these three altered retarder characteristics is to maximize the uniformity of panchromatic transmission through the optical system.
The above-discussed improvements address many deficiencies of the display

apparatus described in U.S.P.N. Re. 27,356. In addition, the design of Figure 1 also addresses the low transmission value experienced on account of system attenuation of an image source, such as cathode-ray tube face 28. A basic change in the optical design addresses this issue with a resultant increase in theoretical transmission to approximately twelve and one-half percent, although actual values will be somewhat less due to inherent losses in the various optical elements, particularly polarizing optical elements 12 and 26.

In Figure 1 the basic arrangement of the improved optical design for a collimator 10 is shown. The system may employ a plurality of image sources, which may comprise a cathode-ray tube (CRT) face 28, a projection screen, models, various types of projectors, or the like, or combinations of the same. For example, the image may first be projected upon a suitable screen. When a CRT is used as the image source, a screen may not be necessary, and the image projected on the face 28 of the CRT produces light 30 having both horizontal and vertical components. The first two elements after the screen or CRT is linear polarizer 12, which outputs vertically polarized light 32. Vertically polarized light 32 is sent to a one quarter wave retarder 14 which outputs right or clockwise circular polarized light 34.

Both linear polarizer 12 and quarter wave retarder 14 are located on the convex side of spherical beam splitting mirror 16. Linearly polarized light 32 from first linear polarizer 12 is converted to right (or clockwise) circularly polarized light 34 after passing through first quarter wave retarder 14. A portion 36 (typically fifty per cent) of this circularly polarized light then passes through the spherical beam splitting mirror 16. Spherical beam splitting mirror 16 can be an actual spherical optical element or alternatively can be a holographic equivalent as described in United States Patent No. 3,940,203.

Circularly polarized light 36 then passes through second one quarter wave retarder

22 and exits as vertically polarized light ray bundles 38. As can be seen in Figure 1, quarter wave retarder 22 is located on concave side of spherical beam splitting mirror 16. As a result of passing through second one quarter wave retarder 22, circularly polarized light 36 is converted to linearly polarized light 38, which is then incident on a reflective-transmissive polarizer 24, oriented such that vertically linearly polarized light 38 is reflected back as light ray bundles 40 through second one quarter wave retarder 22 to emerge as right circularly polarized light 42. Thus, quarter wave retarder 22 has again converted the linearly polarized light to circularly polarized light which is then partially transmitted and partially reflected by spherical beam splitting mirror 16.

A reflective-transmissive polarizer is an optical element that will reflect linearly polarized light aligned with a particular axis of the reflective-transmissive polarizer and will transmit linearly polarized light that has its plane of polarization oriented at 90 degrees to the polarization plane of linearly polarized light that is reflected by the reflective-transmissive polarizer.

Portion 44 of the light that is reflected by spherical beam splitting mirror 16 is now collimated forming an image with focus at infinity (i.e. a collimated image appearing to originate at infinity, or at least a comparatively great distance). This is the case because the distance between light emitting CRT screen or face 28 and reflective-transmissive polarizer 24 plus the distance between reflective-transmissive polarizer 24 and convex mirror 16 is approximately equal to the focal length of convex mirror 16.

This collimated, left (or counterclockwise) circularly polarized light 44 then passes through second one quarter wave retarder 22, where it emerges as horizontally linearly polarized light 46. In other words, the plane of linear polarization is now at

90 degrees with respect to the linearly polarized light that resulted from circularly polarized light 38 and 40 that passed through spherical beam splitting mirror 16, and that first passed through second quarter wave retarder 22. This collimated horizontally linearly polarized light 44 now passes through reflective-transmissive polarizer 24 as light 48, which forms the image to be viewed.

If desired, optional polarizing filter 26 may be used to filter the light a second time to produce light 50 to the eye 52 of a user. A polarizing filter 26 has the effect of removing unwanted stray and feed-through images, such as vertically polarized light which may travel directly from face 28 through optical elements 12, 14, 16, 22 and 24 and light entering the optical system from the direction of the user 52 traveling towards the reflective transmissive polarizer 24.

Besides the greater transmission value of the improved apparatus, there is also a reduction in the intensity of ghost images inherent in display devices of this type due to "bleed through" of the original uncollimated image that is incompletely rejected by the various polarizers. The effect of these ghost images can be further reduced by either using an "off axis" or "tilted" optical design as described in United States Patent No. 4,163,542 as an alternative or in addition to employing final linear polarizer 26 positioned to receive the output of reflective-transmissive polarizer 24 as shown in Figure 1.

The preferred materials for the manufacture of this improved display apparatus are liquid crystal materials. These materials allow the production of reflective-transmissive polarizers of sufficient size and quality to make large displays practical while avoiding the seams and other problems associated with more traditional materials. Use of the liquid crystal materials for the one quarter wave retarders in the improved apparatus also allows the same techniques to be used for the

fabrication of the above structures for correction of darkened areas due to angle of incidence considerations on the one quarter wave retarders to be applied to the improved apparatus. For some display devices it may be more convenient to use one quarter wave retarders, linear polarizers and reflective/transmissive polarizers that are not manufactured using liquid crystal materials, for example wire grid type reflective-transmissive polarizers.

As illustrated in Figure 2, optical elements 12, 14, 16, 22, 24 and 26 may be held within a frame 54.

Because liquid crystal materials or other similar materials can be directly coated on the various optical elements, an alternate and potentially more compact embodiment of the improved collimator 110 may be produced, as illustrated in Figure 3. In the embodiment of Figure 3, polarizer 112, reflective-transmissive polarizer 124 and polarizer 126 perform substantially the same function as polarizer 12, reflective transmissive polarizer 24 and polarizer 26 in the Figure 1 embodiment. However, quarter wave plates 14 and 22 are replaced by quarter wave coatings 114 and 122 coated directly on convex mirror 116.

In accordance with the invention, it may be desirable to remove the polarization characteristic of the output of the collimator 10 or 110. This allows the simulator to be used with systems that have polarization characteristics, such as certain types of helmet-mounted head-up displays, polarizing sunglasses, and so forth. To this end a pseudo-depolarizer may be used. Several birefringent retarders placed in series at various angles to one another have the effect, on an incident beam of linearly polarized white light, of making different wavelength components to emerge with different polarization forms. The polarization states of the emerging beam are so diverse that the beam has many characteristics of an unpolarized beam. Such stacks

of retarders may be used to "depolarize" light. While light of any one wavelength remains polarized, the combined effect of all wavelengths roughly simulates depolarization. Such a stack is thus known as a pseudo-depolarizer. Such a pseudo-depolarizer 56 may be used to adapt the inventive system to use with such accessories having a polarizing characteristic or sensitivity. Pseudo-depolarizer 56 comprises a stack of chromatic retardation plates several hundreds of microns thick so that the light output is comprised of a large number of polarization states resembling unpolarized light.

Another improvement in the new optical design described above is the use of a projection source that is linearly polarized. In this case, the projection screen is made from typical screen materials which diffuse the polarized light from the projector essentially resulting in non-polarized light, is replaced with a screen fabricated with liquid crystal materials such that the direction of diffusion is controlled, thereby largely maintaining the linear polarization of the projector. The fabrication of such liquid crystal screens is made in accordance with conventional techniques and forms no part of the present invention. This approach also allows the elimination of the first linear polarizer on the convex side of the spherical beam-splitter which results in a greater overall transmission value for such systems. While it is most convenient to fabricate the improved projection screen utilizing liquid crystal materials, any method of fabricating a screen with a controlled direction of diffusion sufficient to largely maintain the polarization of the projector may be employed.

In accordance with the invention several inventive collimators may be tiled or stacked to cover larger areas than can be covered by a single collimator. The result is to synthesize a larger collimator than would otherwise be possible.

While an illustrative embodiment of the invention has been described, it is, of

course, understood that various modifications may be made without departing from the spirit and scope of the invention, which is limited and defined only by the appended claims. For example, one or more of the optical members may be replaced by flat sheets incorporating a holographic optical element and the entire assembly sandwiched together to form an exceedingly thin package. In addition, additional images from additional image sources may be introduced into the simulation created by the inventive system through the use of beam splitter mirrors interposed at an angle of 45 degrees in the optical path of the simulator so that the beam-splitter mirrors reflect light from the additional image sources along the optical path toward the observer. Such modifications are within the scope of the following claims which define the invention.